Introduction

As humans, we are exquisitely tuned to voices and all that they are capable of conveying (Table 1). On hearing someone speak, we quickly infer details about gender, age, education, and geographical background (Sebastian and Ryan, 1985). We listen for signs of interest, well-being, competence, and cooperation, or coldness, ineptness, and resistance. Along with these, mood, emotional conditions, personality, and psychological status are simultaneously assessed by the listener, with varying accuracies. These speaker characteristics constitute a very large, complex array and pose huge challenges to analytic approaches.

Not least important among the characteristics listeners extract from voices is the identity of the person who is speaking. The person may be someone familiar; or, much less commonly, we may try to identify a stranger, for example in a forensic situation. In this paper we will describe some of the important differences between these two classes of stimuli—familiar and unfamiliar voices—and the cognitive and neuropsychological processes used in their perception. We then present a preliminary model of the manner in which listeners tackle each kind of information, taking account of underlying brain structures involved in these disparate processes. Finally, we explore the implications of our model for measurement of quality in the voice clinic and elsewhere.

Which came first: Familiar or unfamiliar voices?

Unfamiliar voices surround us in life, from the sound of the cashier greeting us at the market, to students talking in the hall outside a classroom, to the voices of other patrons conversing in a background of chattering and cheering at a sports event. When we pay attention to such voices, they can provide substantial amounts of information about the speaker, as noted above, and as a result it is easy to assume (as we ourselves have done in the past) that the unfamiliar voice is somehow the basis of the perceptual processes used to extract information from all voices. After all, we reasoned, every voice was unfamiliar before it was familiar, so logically familiarity develops out of unfamiliarity, which implies that the unfamiliar is foundational.

In the beginning was the familiar voice

A substantial body of evidence suggests that the assumption that unfamiliar voices are fundamental is fundamentally wrong. First, we note that the ability to recognize a familiar voice (and especially the voice of a parent, offspring, or mate) is very widespread among animals. Many, many species, including deer (Torriani et al., 2006), sheep (e.g., Sebe et al., 2010), wolves (Goldman et al., 1995), mares (Wolska et al., 1980), many marine mammals (e.g., Insley, 2001; Pitcher et al., 2010), rodents (Fuchs et al., 2010), bats (Voigt-Heucke et al., 2010), amphibians (Bee and Gerhardt, 2002; Simmons, 2004), and birds ranging from penguins (e.g., Jouventin and Aubin, 2002) to parrots (Berg et al., 2011) also recognize the familiar voices of their kin. Recognition often begins very early in life, or even immediately; for example, the developing human fetus has been shown to recognize the voice of its mother (Kisilevsky et al., 2003). Scientists have only begun to appreciate the social complexity and sophistication of these behaviors. Recent studies reveal that seal mothers time their departure for food gathering to coincide with successful voice recognition by their pups, so that reuniting on their return will be successful (Charrier et al., 2001). In comparison, mother evening bats recognize the voices of their normal. The wide distribution of voice recognition abilities across species, combined with the clear survival value of such abilities and their strikingly full-blown ontogenetic appearance, suggests that familiar voice recognition is evolutionarily very old.”

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Voices and Listeners: Toward a Model of Voice Perception

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voices of their offspring immediately after birth, suggesting calls have a genetic component (Scherrer and Wilkinson, 1993). These biological scenarios cast an eerie doubt on the traditional assumption that all voices, at the first instant, are unfamiliar.

Voice recognition facilitates reunions between foraging parents and offspring that are mobile or located in a crowded crèche, helps animals ensure that care is provided to the correct infant, and promotes bonding between mothers and infants. The wide distribution of voice recognition abilities across species, combined with the clear survival value of such abilities and their strikingly full-blown ontogenetic appearance, suggests that familiar voice recognition is evolutionarily very old. In fact, it may have appeared by the time that frogs emerged (Burke and Murphy 2007; Bee and Gerhardt, 2002; see Kreiman and Sidtis, 2011, for more review). Studies showing that primate brains may have voice-sensitive areas analogous to those seen in human infants as young as 7 months (Petkov et al., 2008; Petkov et al., 2009; Grossmann et al., 2010) further point to a long evolutionary history of voice recognition abilities (Belin and Grosbras, 2010). Producing and recognizing familiar voice patterns thus antedates, by millions of years, the more lauded evolutionary development of speech and language in human communication and cognition. For discerning cohort, friend from foe, and recognizing intimate family members—and being able to achieve this at a distance and in the dark—the preeminence of the familiar voice pattern in evolutionary biology can hardly be exaggerated (Sidtis and Kreiman, 2011).

Recognition of the familiar voices of animals that are not first-degree relatives is less common, but helps maintain proximity and promotes group cohesion in social animals by providing a means of separating insiders from outsiders, even at a distance (Fig. 1). For example, female vervet monkeys can recognize the voices of their own offspring but also of unrelated juveniles, and can associate those voices with the correct mother (Cheney and Seyfarth, 1980); and female baboons recognize both the screams and threat grunts of unrelated individuals (Cheney and Seyfarth, 1999). Playback experiments (in which recorded vocalizations are broadcast in the field to freely-behaving animals and responses are recorded) have shown that the extent of elephants’ defensive responses (bunching together, retreating) to the voices of elephants from the other family groups encountered within their range can be predicted by the frequency with which those animals are encountered. Response patterns imply an ability to recognize about 100 individuals (McComb et al., 2002). In the vast landscape of biological vocal recognition, not to be neglected is the ability of nonvocal reptiles to recognize alarm calls of other species (Vitousek et al., 2007). Although these abilities are impressive, they pale in comparison to prodigious human abilities to recognize the voices of people we are not related to. Besides our friends, family, neighbors, and other associates (the “familiar-intimate” set), thanks to the media we are easily able to recognize and identify scores of people we have never spoken to or even met (the “familiar-famous” voices: actors, politicians, announcers, broadcasters), as well as fictional beings of endless variety (Bugs Bunny, Hal the computer, and Robby the Robot, for example). In fact, studies of familiar face recognition (Bahrick et al., 1975) and informal voice recognition challenges suggest that there may not be an upper limit to the number of voices humans can recognize (Ladefoged and Ladefoged, 1980).

In contrast, it is not clear how much attention listeners of any species actually pay to unfamiliar voices under normal circumstances. Most animals, including humans, treat unfamiliar voices as part of the background of noise that surrounds them every day. As an example, imagine yourself on a busy street, surrounded by strangers talking to each other or on their cell phones. The voices we hear under these circumstances, though ubiquitous, barely penetrate consciousness. In fact, in a study in which the original caller was surreptitiously replaced with a different talker during a telephone survey call, only 6% of subjects noticed the change (Fenn et al., 2011). In contrast, the voice of an approaching friend jumps out from a background of unknown voices, much as the sound of our own name emerges from the unattended
chatter in a crowded room. From these several perspectives, we must conclude that it is the familiar voice pattern that plays the dominant role in animal biology and human culture (Sidtis and Kreiman, 2011).

The brain behind the voice

These findings suggest that there should be differences in the neuropsychological and cognitive processes involved in perceiving familiar versus unfamiliar voices. That is, if recognizing a familiar voice is “basic” in some way, we might expect that there exist specific, efficient neuropsychological mechanisms to support this ability. Similarly, if unfamiliar voices are not important or salient stimuli, we might expect a messier set of processes to be engaged if and when we are forced to deal with them.

In fact, a substantial number of studies point to such differences. Recognizing a familiar voice and discriminating among unfamiliar voices are dissociated neuropsychological abilities, meaning that either one can be independently disrupted by neurological damage, leaving the other entirely intact (Van Lancker et al., 1987). Familiar voices engage a large expanse of cerebral systems. Upon recognizing a familiar voice, parietal lobes establishing associations in declarative memory, subcortical structures modulating memory, motivation and emotion, frontal lobes organizing and integrating behaviors, and temporal lobes processing auditory patterns and selected auditory features all participate (see Kreiman and Sidtis, 2011, for extended review). Although multiple cerebral structures play significant roles in processing familiar voices, studies of performance following brain lesions and in functional imaging give a role to the right cerebral hemisphere as a final common pathway for voice recognition, especially of familiar stimuli (e.g., Van Lancker et al., 1989; Neuner and Schweinberger, 2000; Belin et al., 2000; Latinus and Belin, 2011b; Gainotti, 2011).

Consistent with right hemisphere participation in familiar voice perception and recognition, evidence suggests that familiar voices comprise distinctive, integral, heterogeneous patterns, which can be accessed as unique, holistically stored units. These integral patterns resist systematic decomposition into bundles of separable features. Parameters like F0, timbre, and intensity—cornerstones of voice quality analysis—interfere with each other perceptually, such that irrelevant, unattended variation on one parameter facilitates or interferes with listeners’ judgments of the other, depending on whether that irrelevant variation is or is not correlated.

Fig.1. Some non-human animals that recognize the voices of familiar non-family members. A: vervet monkeys. B: baboons. C: elephants.
with the attended dimension (Melara and Marks, 1990; Li and Pastore, 1995). Similarly, studies using unfamiliar voices show that the harmonic and inharmonic (noise) parts of the voice interact perceptually, so that listeners’ sensitivity to either depends on energy levels in both (Kreiman and Gerratt, in press); and sensitivity to tremor rates in voice depends on the magnitude of the tremor, and vice versa (Kreiman et al., 2003). Further, listeners’ relative inability to reliably and consistently isolate single dimensions in a voice pattern is the largest source of error in voice quality ratings (Kreiman et al., 2007). These findings argue against reliance on feature-based models of voice quality of the sort that underlie most clinical voice evaluation protocols (about which more in a moment). As most studies of voice and voice quality perception use unfamiliar voices as stimuli, understanding the functional and perceptual roles of auditory-acoustic cues or features in the perception of familiar voices has only been crudely begun (Van Lancker et al., 1985).

These early attempts have shown that individual familiar voice patterns vary greatly in how (and how much) cues such as F0 or breathiness contribute to the recognition process. While familiar voice recognition engages pattern recognition processes of the right hemisphere, discriminating among unfamiliar voices or “identifying” a voice heard only once or twice before (for example, in a voice lineup) engages auditory temporal receiving areas on both sides of the brain (Van Lancker et al., 1989), and seemingly involves both pattern recognition and featural analysis/matching skills. Error patterns in long-term memory tasks suggest that unfamiliar voices are encoded in terms of a generalized template or “prototype,” along with a set of deviations from that prototype which are forgotten over time so that memory tends to converge on average-sounding voices no matter what voice was heard originally (Papcun et al., 1989). Similarly, memory tests in change deafness studies (testing listeners’ awareness of abrupt voice quality changes during normal interaction) suggest that listeners remember only coarse differences between unfamiliar voices under normal circumstances (a “gist-based” representation, Fenn et al., 2011, p. 1454), and that memory for specific acoustic details of a voice may be weak or entirely absent. In contrast, for familiar voices, a complex, unique perceptual pattern is stored along with an array of personally-relevant associations (appearance, biographical and episodic history, affective nuances, and so on); recognition occurs within a second or two; and the “cues” triggering recognition vary widely with vocal pattern (Schweinberger et al., 1997a). These findings have led us to conclude that all voices are fundamentally patterns, and that pattern recognition and featural analysis reciprocally operate, in different degrees, for all voice perception processes, depending on the status of the voice with respect to its familiarity to the listener.

A large body of behavioral evidence also supports the notion that voices are best viewed as patterns. In a “repetition priming” protocol, listeners’ accuracy in judging whether or not a voice sample was famous improved when they had previously heard a different sample of the target voice, so that the advantage transferred between tokens of speech and did not depend on the specific acoustic details of an individual sample (Schweinberger et al., 1997b). Adaptation studies provide similar evidence. In these studies, the experimenter creates a stimulus continuum by “morphing” between two voices—for example, those of a male and a female. When listeners hear tokens taken from one end of the continuum, their judgments of ambiguous stimuli from the middle of the continuum shift, so that hearing a relatively male sample 3 or 4 times makes the ambiguous sample sound more female, and hearing tokens from the female end of the continuum makes it sound more male. These effects have been shown for judgments of speaker identity (familiar voices: Zäske et al., 2010; trained to recognize: Latinus and Belin, 2011a), but also for

Table 2: Some of the factors affecting listeners’ ability to identify an unfamiliar voice

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
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<tbody>
<tr>
<td>The a priori “distinctiveness” of the target voice</td>
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<td>The speaker and listener’s accents and/or the language spoken</td>
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<td>The presence of disguise or mimicry</td>
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<tr>
<td>The duration and phonetic content of the speech sample</td>
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<tr>
<td>Whether or not the same sample is used at learning and test</td>
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<tr>
<td>Filtering (for example, by a telephone or recording)</td>
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<tr>
<td>The listener’s inherent ability to remember voices</td>
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<tr>
<td>The listener’s attention at learning and at test</td>
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<tr>
<td>The listener’s sex</td>
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<td>The listener’s professional training</td>
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<tr>
<td>The delay between hearing a voice and identifying it</td>
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<tr>
<td>The number and kind of distracter voices in the lineup</td>
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<tr>
<td>The instructions the listener receives</td>
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Fig. 2. A fox and a hedgehog.
perception of emotion (Bestelmeyer et al., 2010), speaker sex (Schweinberger et al., 2008), speaker age (Zäske and Schweinberger, 2011), and ratings of roughness (Gerratt et al., 1993) from voice, and are interpreted as reflecting adaptation of a central representation (a pattern), rather than the effects of specific acoustic characteristics of the stimuli. Finally, studies of familiar voice recognition (e.g., Van Lancker et al., 1985) have demonstrated that the acoustic cues to personal identity vary from voice to voice, and the importance of a given cue depends on the context of the complete voice pattern in which that cue operates, and not on the value of the cue itself. Thus, unusual pitch contours or a marked foreign accent (for example) may be essential cues to a speaker’s identity, or not, depending on the other cues that are available to listeners. It is thus impossible to devise a set of features that are important for recognition of all voices: The importance of a given cue depends on the pattern in which the cue appears and on the status of the voice as familiar—and stored as a personally relevant auditory object—or unfamiliar and handled perceptually in terms of stereotypes or generalized templates.

One final difference between familiar voice recognition and unfamiliar voice discrimination is that familiar voice patterns are remarkably robust, so that we can recognize a familiar voice in noise, based on very short samples (often just the word “Hi” on a band-limited telephone line), even when the voice has not been heard for years or even decades and has changed with time (voices appear to change less with age than do faces). In contrast, virtually anything will disrupt efforts to match an unfamiliar voice to a decaying memory trace. Studies (primarily focusing on forensic situations) have shown that identification scores fluctuate as a function of a wide range of factors characterizing the speaker, the listener, and the circumstances surrounding originally hearing and subsequently identifying the voice, (Table 2; see Bricker and Pruzansky, 1976, or Kreiman and Sidis, 2011, for review). It appears that the greater the reliance on featural extraction, comparison, and analysis, the worse we are at the task.

Features and patterns: A “fox and hedgehog” model for voice recognition

Taking an idea from the essay of Isaiah Berlin (1953) on Archilochus’ fable about a fox and a hedgehog (Fig. 2), we have proposed a model of voice perception that suggests voices can be recognized by varying applications of featural and pattern recognition processes. In the fable, the fox knows many little things while the hedgehog knows one big thing. There are many versions of the bipolarity expressed in this adage: empiricism contrasted with rationalism, Aristotle meets Plato, behaviorism compared with the sweeping ideologies of cognitive science, agility of thought versus persistence (Gould, 2003). In our model of voice perception, the aphorism is meant to represent the interplay between features and patterns in the speaker-listener interface. Some voices and some voice perception tasks draw more heavily on features (many little things), while other voices and other tasks utilize pattern recognition abilities more heavily. This counterpoint helps elucidate the respective roles of unfamiliar and familiar voices, in that featural elements figure importantly in the discrimination of unfamiliar voices (in the sense of matching to generalized templates), while overall pattern recognition predominates for familiar voices (in accessing unique auditory percepts).

Measuring voice quality

We have argued thus far that humans are good at familiar voice recognition because we have inherited this ability through our evolutionary past, and that familiar voices are best treated as integral patterns. Nevertheless, most approaches to voice quality assessment depend on the use of

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<tr>
<td>Clear (claram)</td>
<td>Clear, light, white</td>
<td>Clear</td>
</tr>
<tr>
<td>Deep (gravam)</td>
<td>Deep</td>
<td>Resonant, low</td>
</tr>
<tr>
<td>Brilliant (splendidam)</td>
<td>Bright, brilliant</td>
<td>Bright, vibrant</td>
</tr>
<tr>
<td>Smooth (suavam)</td>
<td>Cool, smooth, velvety</td>
<td>Smooth</td>
</tr>
<tr>
<td>Attractive (illecebrosum)</td>
<td>Pleasing</td>
<td>Pleasant</td>
</tr>
<tr>
<td>Dull (fuscem)</td>
<td>Dead, dull, heavy</td>
<td>Dull, heavy, thick</td>
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<tr>
<td>Thin (angustam)</td>
<td>Constricted, heady, pinched, reedy, shallow, thin</td>
<td>Thin</td>
</tr>
<tr>
<td>Harsh (asperam)</td>
<td>Harsh, strident, twangy</td>
<td>Harsh, gravelly</td>
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<td>Unsound, hoarse (infirmam, raucam)</td>
<td>Faulty, hoarse, poor, raucous, rough</td>
<td>Hoarse, rough, labored, noisy</td>
</tr>
<tr>
<td>Brassy (aenam)</td>
<td>Buzzy, clangy, metallic</td>
<td>Metallic</td>
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perceptual or acoustic features for quality, or both—in other words, on approaches that use processing strategies that resemble those we apply to unfamiliar voices, with which we are considerably less adept. For example, many authors have proposed lists of descriptive terms to assess quality, and listeners typically measure quality by indicating the extent to which a voice possesses each feature (Voiers, 1964; Gelfer, 1988; Ishihiki et al., 1969; Kempster et al., 2009). This approach (the only one currently available for quantifying quality), replete with redundancies and ambiguities, arises from 2000 years of tradition rather than from theory. Many of the features commonly in use today—for example, harsh, breathy, clear, bright, smooth, weak, shrill, deep, dull, and hoarse—can be traced to Roman writings on oratory (Table 3; Laver, 1981; Austin, 1806). Because assessing voices on such rating scales requires listeners to analyze a vocal pattern into component features, we might expect listeners to have a great deal of difficulty using such quality measurement protocols, and in fact many studies have shown quite low levels of interrater agreement, as predicted (see Kreiman et al., 1993, for review).

Nevertheless, quantifying voice quality is essential to many endeavors, including studying the efficacy of treatments for voice disorders or the acceptability of speech synthesis efforts. This leaves us with the following problem: How do we quantify an unanalyzable pattern? One solution under investigation (Gerratt and Kreiman, 2001; Kreiman et al., 2007) is the use of an analysis-by-synthesis approach in which voices are copied using a voice synthesizer specialized for replicating variations in voice quality. Because the complete voice pattern is copied exactly, the synthesizer parameters explicitly link a range of selected features of the acoustic signal to the overall, integral pattern, and can thus be used validly as objective acoustic indices of subjective perceptual responses. Because this method allows us to study how listeners manage the interplay between features and patterns, it allows for applicability to both familiar and unfamiliar voices and holds the promise of elucidating their distinctive dynamic processing characteristics.

The larger universe of perceptual judgments

Speakers make judgments regarding physical, psychological and social characteristics from voice that go well beyond mere speaker identity, and we are only beginning to understand the range of information conveyed and the manner in which such information is extracted and exploited. For example, the emotional and attitudinal nuances conveyed by voice may well number in the thousands; and many animals (including possibly humans) are adept at extracting information related to reproductive fitness from vocal signals (e.g., Hardouin et al., 2009; Charlton et al., 2007; Apicella and Feinberg, 2008). Thoughtful examination of everyday talk reveals an immense set of possible judgments listeners may make (Table 4). This is not an exhaustive list, but is intended to point to the potentially large constellation of characteristics that underlie functional voice perception. It becomes clear that a systematic reductionist approach to the study of voice perception in the face of these many variables is unre-
alistic; yet dismissal or rejection of all but a few characteristics holds little promise of explaining voice perception. It has become obvious in inspecting the array of potential cues that not all will pertain to the successful perception of a given voice pattern. Instead, some emerge as decisive to perception of a pattern, and most will be irrelevant.

Drawing on the perspective that individual voice patterns are singular and unique, we propose a model of voice perception that allows for interplay between characteristics or features and the signature voice pattern. Our model is based in the interactivity of voices and listeners in all of voice perception, and takes into account three continua—the relative contributions of feature and pattern recognition processes to recognition or perception of different sorts of voice patterns; differences in the neurological and psychological status of familiar and unfamiliar voices; and left versus right cerebral hemisphere processing and the contributions of subcortical systems in the brain. Perception of the myriad vocal characteristics communicating physical and personality cues, mood, emotion, attitude, background and so on is likely to differ significantly with the relationship of the voice to the listener—that is, its status as familiar or unfamiliar. While deconstruction of neutral voice samples will yield fascinating details about acoustic structure, it is taking on the challenge of the talker-listener interaction with a personally familiar voice pattern and its complex indices of information that will lead to fruitful studies of this immense natural endowment.

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